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AVACTA II MODEL SIMULATIONS OF WORST-CASE AIR POLLUTION SCENARIOS IN NORTHERN ITALY

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INTRODUCTION AND OVERVIEW

This paper presents a new, improved version of the AVACTA II air pollution computer package, its numerical and analytical features, and its simulation capabilities and limitations. This is followed by the presentation of a few AVACTA II simulations of worst-case air pollution scenarios in northern Italy, a region characterized in wintertime by foggy, stagnant conditions often leading to air pollution episodes in the Po Valley (Val Padana).

The current version (Release 3) of the AVACTA II code uses a new mixed methodology which provides a more realistic and cost-effective simulation of short-term (i.e., from a few hours to a few days) air pollution phenomena than its predecessors while still maintaining the simplicity of the basic Gaussian dispersion formula. The model can be applied, with appropriate meteorological and emission input, to short-range, intermediate, and, most importantly, long-range simulations. It provides a prediction of the concentration and dry/wet deposition fields for virtually any pair of primary-secondary pollutants (e.g., SO_2 and $SO_4^=$).

The importance of air pollution models and their continuous development and improvement, especially in the United States and Europe, is dictated by their being the only tool which establishes a quantitative, deterministic relation between pollutant anthropogenic emissions and ambient concentrations. This feature is very important for both research applications and regulatory (e.g., source permitting and evaluation) activities.

Diffusion models are either based on simple physical assumptions (e.g., the Gaussian models), or on complex methodologies (e.g., higher-order closure or Lagrangian particle models). Neither the simple nor complex approaches, however, have provided satisfactory simulation results when used for short-term (e.g., hourly) dispersion simulations (Liu and Moore, 1984; Reynolds et al., 1984a; Reynolds et al., 1984b; Lewellen and Sykes, 1983; Ruff et al., 1984). Moreover, the conclusions of several studies (e.g., those recently presented at the DOE Model Validation Workshop, October 23-26, 1984, Charleston, SC) indicate that the more advanced numerical techniques, when applied in a hands-off way, do not perform better than simpler numerical approaches and, therefore, have not yet justified their computational cost in terms of simulation performance.

The above findings indicate the need for additional air pollution modeling efforts to improve the existing simulation capabilities and provide the numerical answers to the recent environmental problems (e.g., acidic deposition) posed by the expanding worldwide urban and industrial activities. Future model development efforts are expected to focus on 1) the development and application of more complex and sophisticated methodologies, which will certainly require more advanced meteorological information than routinely available today; and 2) the improvement of the simulation capabilities and semi-empirical parameterizations of some of the relatively simple numerical techniques currently available. The modeling discussion presented in this paper aims at the latter objective.

THE AVACTA II MODEL

The AVACTA II approach (which is fully discussed by Zannetti, in press) utilizes the Gaussian formula in a dynamic way, in which each plume is described by a series of plume "elements" (segments or puffs) whose characteristics are updated at each "dispersion" time step Δt (e.g., 5-10 minutes), and whose dynamics are a function of time-varying emissions and three-dimensional meteorological fields. The dynamics of each element during each Δt consist of

1. generation, at source's location
2. plume rise
3. transport by advective wind
4. diffusion by atmospheric turbulence
5. ground deposition, dry and wet, and
6. chemical transformation, creating secondary pollutant from a fraction of the primary pollutant

Generation is performed by adding a new element to the element "chain" for each source. All existing element coordinates are advected according to the time-varying average wind vector at the element's location. The element's diffusion is simulated by increasing its σ values based on the virtual distance/age concept (Ludwig et al., 1977; Zannetti, 1981). Deposition is computed by an exponential reduction of the masses of primary and secondary pollutants in each element, according to time-varying rates. Chemical transformation reduces the mass of primary pollutant and increases the mass of the secondary one in each element, using a first-order reaction scheme with a time-varying rate.

Concentration Computation

All the previous computations of the element's dynamics apply to both segments (i.e., sections of a Gaussian plume in which streamline diffusion is negligible) and puffs (i.e., elements with three-dimensional Gaussian distribution). The criterion for identifying the type (segment or puff) of element is the ratio between its length L_e and its σ_h (the standard deviation of the horizontal concentration distribution). For a segment

$$L_e/\sigma_h > 2$$

and for a puff

$$L_e/\sigma_h \leq 2$$

Since σ_h continues to grow with time, all segments will eventually become puffs. The above criterion assures that, when segments grow into puffs, the distance between the centers of two consecutive puffs is not greater than 2 σ_h, which is the condition required (Ludwig et al., 1977) for a series of puffs to provide an almost perfect representation of a continuous plume.

According to the above scheme, during calm or low wind speed conditions, elements are directly generated as puffs, thus providing a realistic and computationally efficient representation of calm, transport and transitional cases. For example, puffs can accumulate for a few hours in the region near the source during calm conditions, and then be subsequently advected downwind when stagnation breaks up.

The concentration at each receptor R due to a source S is computed by the sum of the contributions of all existing puffs plus the contribution of the closest segment. This latter contribution is given by the concentration field produced by the virtual "straight-line" plume passing through the closest segment, where this virtual plume represents the entire contribution of the "segmented" portion of the plume.

During the above concentration computations, numerical problems may arise in two circumstances:

1. when the receptor is close to the point of the plume in which segments grow into puffs

2. when large horizontal displacements of plume elements during Δt do not allow enough resolution in the representation of plume dynamics

The first case is illustrated in Figure 1 and its correct numerical treatment requires, among other assumptions, the elimination of the contribution of the two puffs preceding or following the closest segment (in the case of receptor R_1), and the transformation into puffs of the closest segment and the one eventually adjacent to it (in the case of receptor R_2).

The second case is correctly treated by the splitting technique, which was originally proposed for puff modeling simulations (Zannetti, 1981) and is here extended to both puffs and segments. This splitting generates, when required, a sufficient number of fictitious elements along the element's trajectory during Δt to maintain sufficient resolution, still conserving the element's masses of pollutant, which are equally distributed among the split elements.

The Computer Code

A full description of the AVACTA II software is given in its user's manual (Zannetti et al., 1985). The code gives the user a high degree of flexibility in defining or selecting the computational domain, the three-dimensional meteorological and emission input, the receptor locations, the plume rise computation, the σ functions, and other options. Without explicit user specifications, standard default values and assumptions are used. In particular, the code uses a split-sigma approach in which the horizontal σ_h (frequently indicated by σ_y) evolves according to the horizontal turbulence status (e.g., inferred from wind direction fluctuation intensity measurements) and the vertical σ_z according to the vertical turbulence status (e.g., inferred from vertical temperature gradient information). This approach is very useful, especially

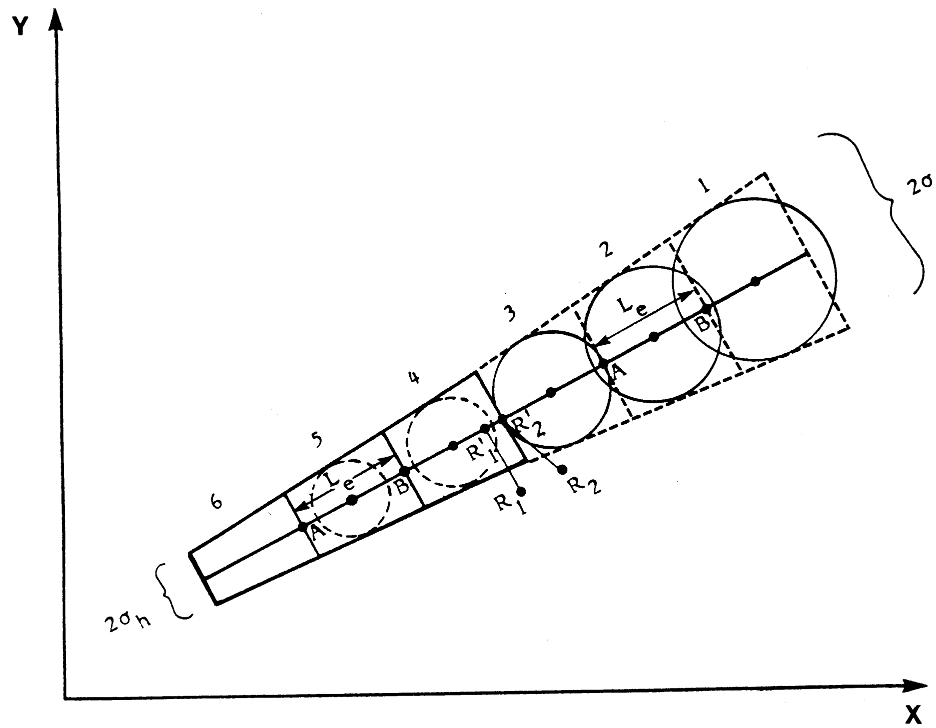

Fig. 1. Chain of elements and special treatment of the transition segment-puff. The contribution of the puffs 2 and 3 is eliminated for computing the concentration in R_1. The two segmeents 4 and 5 are transformed into puffs for computing the concentration in R_2.

during low wind speed conditions, when horizontal turbulence may be almost totally decoupled from vertical turbulence. Different σ functions (e.g., Pasquill-Gifford-Turner, Brookhaven, Briggs, etc.) can be selected by the user for the evaluation of σ_h and σ_z.

Finally, different reflection assumptions can be specified by the user (e.g., through the utilization of the Yamartino, 1977, method); and a three-dimensional, mass-consistent wind field in complex terrain can be optionally generated, from available measurements, for a more accurate evaluation of plume transport in the computational domain.

The output of AVACTA II provides a full set of statistics of the concentration time series simulated at the receptor points (for both the primary and the secondary pollutant), and the dry deposition and wet deposition fields. These statistics comprise hourly concentration values, 3-h and 24-h running concentration averages, and hourly, 3-h and 24-h total highest and highest-second-highest concentrations.

AVACTA II SIMULATIONS

Some preliminary AVACTA II simulations have been performed during stagnant episodic conditions in northern Italy. These simulations represent only the first step in an on-going validation activity that should provide, in the near future, a complete evaluation of the AVACTA II model performance, together with specific recommendations on the choice of its several options.

The simulations presented in this paper deal with two episodic conditions leading to accumulation of SO_2 in the region under investigation. During the first episode an SF_6 tracer release experiment was also performed, which provided further insight on atmospheric dispersion characteristics during these peculiar conditions.

The Modeling Region

The modeling region is the area near Turbigo, on the northern side of the Italian Po Valley, which is affected by the SO_2 emissions from a multi-unit local oil-burning power plant. The area is in gently rolling complex terrain and, during winter, is also affected by local urban heating emissions, which complicate the evaluation of source-receptor relationships.

The Turbigo area has been chosen by the Italian National Electric Power Industry (ENEL) as a test site for the installation of an advanced meteorological and air quality monitoring system, with real-time computerized data gathering features. Among the various hardware equipment in the area are a Doppler Acoustic Sounder, a radioacoustic sounder RASS (providing very reliable temperature profiles from 80 m up to over 1,000 m with a 12 m resolution), a flux meter, several wind stations and five ground-level SO_2 monitoring stations.

Moreover, the Turbigo area has been frequently selected for national and international (European Community) SF_6 tracer field experiment activities.

The Local Meteorology

The Po Valley portion of northern Italy is characterized during wintertime by frequent stagnant and foggy conditions, often associated with low, elevated subsidence inversions. Due to the complexities of the terrain, nighttime downslope and, especially, daytime upslope valley breezes are quite frequent. Typical daytime breezes are 3-4 m/s while nighttime values are lower (2-3 m/s). The depth of the breeze layer is between 400 and 600 m. More detailed meteorological information has been presented by Anfossi et al. (1980).

The Simulation Experiments

An SF_6 tracer experiment was performed on 22 January 1982 in the Turbigo area during foggy conditions and a strong elevated subsidence inversion ($\Delta T/\Delta z \simeq 4.5\ ^{o}C/100$ m) with a base at about 150 m (see the RASS temperature vertical profile at 4 p.m. in Figure 2). The SF_6 tracer was released from the three operative stacks of the Turbigo power plants from 1 p.m. to 4 p.m., maintaining a constant ratio (1/80) between SF_6 and SO_2 emission in each stack. Ambient concentration data were collected from 34 SF_6 monitors and five SO_2 stations (30-minute averages).

The AVACTA II model was applied for simulating both SF_6 and SO_2 dispersion. Doppler Acoustic Sounder wind measurements were used for evaluating the wind vertical profile input for the divergence-free wind generation routine. Atmospheric stability was evaluated from RASS temperature profiles. The comparison between AVACTA II outputs and measured concentrations (30-minute averages) at all receptors showed limited simulation capabilities, mainly due to the large uncertainty in evaluating the three-dimensional variation of the wind direction parameter during the experiment (which was characterized by very low winds: 1-2 m/s).

The model, however, showed some capability of evaluating (about half of the time) the maximum SF_6 concentration impact within a factor of two (but not necessarily at the same location where the maximum was measured). Results were very irregular and 30-minute periods with very high measured-computed correlation (e.g., 0.7-0.9, considering all the receptors with nonzero measured concentration) were followed by periods with practically zero correlation. The general tendency of the model was to overestimate ground-level concentration (using either Pasquill-Gifford sigmas or Brookhaven or Briggs open-country). Results seem to indicate that the actual horizontal diffusion is much greater than the simulated one, thus leading to frequent overevaluation of concentration impact.

The comparison between SO_2 measured and simulated concentrations showed a similar behavior, even though two consecutive 30-minute intervals were characterized by very high (> 0.9) measured-computed coefficients. Maximum SO_2 concentration impacts tended to be overevaluated by a factor of two to three.

A second simulation test of model performance was performed for a two-day period (November 4-5, 1981), which was characterized by a severe air pollution episode in the region: foggy conditions, 98% relative humidity and a strong subsidence elevated inversion (150 m on November 4 and 450 on November 5). The results were similar, as before, with a tendency to an even greater overprediction of SO_2 ground-level impacts.

Model results cannot be considered very satisfactory and clearly show the need of more calibration effort for obtaining a better physical representation of these stagnant situations.

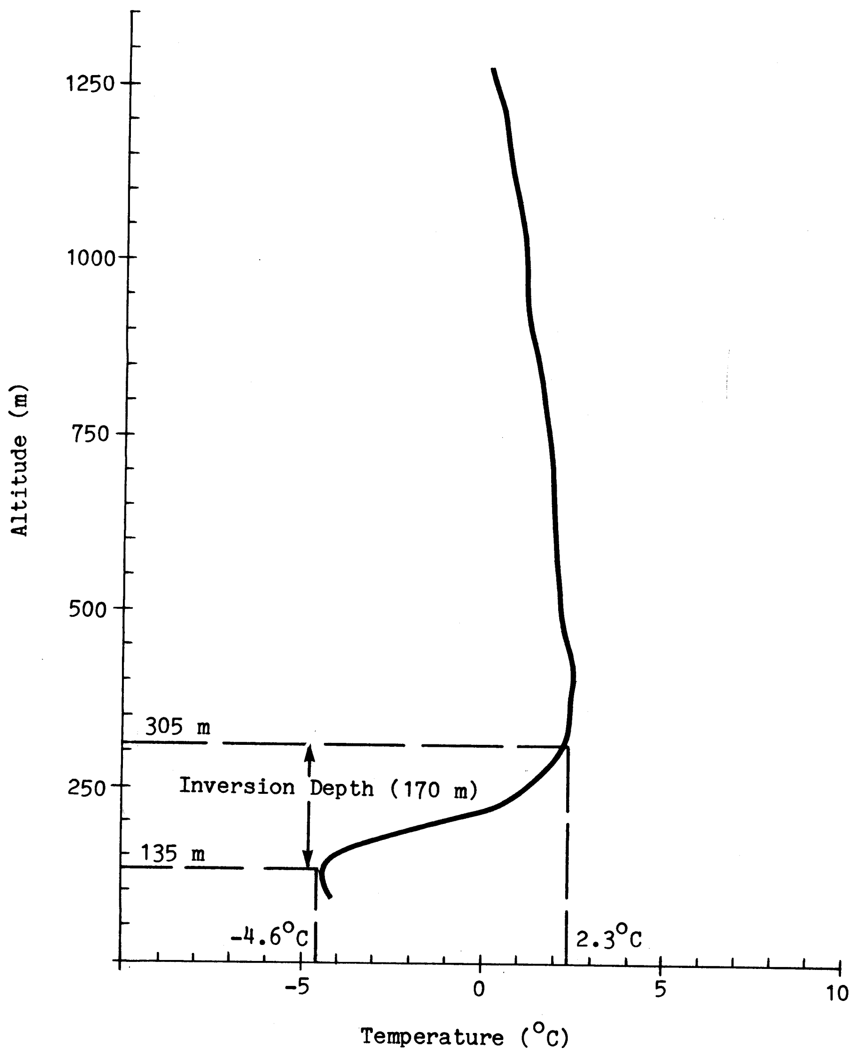

Fig. 2. Radio acoustics temperature profile, January 22, 1982, local time 16:00.

CONCLUSION

The preliminary simulation results presented above confirm the difficulties in simulating episodic situations with low wind speed, even when improved modeling techniques and advanced remote sensing meteorological data collection methods are used. In particular, the patterns of the ground-level "fingerprints" from elevated tracer releases are extremely complex, to a point that stochastic semi-random fluctuations seem to represent a predominant factor.

A full performance evaluation of AVACTA II, however, requires 1) more evaluation and calibration efforts and, especially, 2) a comparison of AVACTA II outputs with those of other models, to evaluate the relative performance of this new approach. Future studies are expected to provide additional results on these two issues.

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DISCUSSION

P. BARRY

In how many locations did you measure the wind speed and directions?

P. ZANNETTI

Wind was measured by a meteorological station and a Doppler Acoustic Sounder. These input data have been extrapolated and numerically adjusted in order to generate a 3 D divergence free wind field.

D. ROSS

How does your model handle transport of the puffs or segments in regions of shear or convergence/divergence of streamlines ? Do you just advect the centroid of the puff or allow puffs to shear or split ?

P. ZANNETTI

In the present version of the code we just advect the centroid of the puff. However, this advection is performed by considering the average wind vector in the current volume occupied by the puff. Moreover, when necessary, puffs are allowed to split along their trajectory to maintain a good plume resolution.